NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

Pinching-free connector for seismically-resistant timber structures: experimental validation and numerical simulation

N. Chan, A. Hashemi & P. Quenneville
University of Auckland, New Zealand.

P. Zarnani
Auckland University of Technology, New Zealand.

ABSTRACT

The philosophy when designing timber connections is to use many small-diameter fasteners to achieve a minimum amount of ductility. However, even if brittle failure of the timber is prevented at the joint, the yielding failure of the timber/fastener combination will include an increased amount of pinching at every subsequent cycle. In the paper, a new connector is presented that prevents this pinching behaviour. The main principle of the connector is based on eliminating the “slack” that occurs at every load cycle. This offers the advantage that the joint fasteners, even in their bent state, can mobilise the full energy-absorbing capacity of the embedment of the timber so that the governing failure mode becomes Mode-I of the European Yield Model. An experimental demonstration was conducted to show that slender fasteners cross-over from failure Mode-II/III initially to Mode-I eventually, attaining the load plateau without pinching. With stocky fasteners, the response on every loading cycle was repeatedly stiff and at a consistent Mode-I capacity. In this configuration, a displacement ductility of 10 was achieved. This connection was compared to ordinary brackets via numerical simulations of a rocking shear wall subjected to 10 ground motions. The PFC reduced peak displacements by a factor of 3 on average and substantially muted the post-peak vibrations. This contrasted with larger swings in displacements of the ‘loose’ bracket connection possessing slack. This connector has the potential to alter the design philosophy of using many small dowel-type fasteners in timber connections to offer a ductile connection.

Paper 63

1 BACKGROUND

Building structures are occasionally subjected to extraordinary loads, such as during earthquakes. Structures are presently designed to cope with these loads without catastrophic failure. However, damage to the structure or parts of the structure is inevitable, and to an extent desirable or intended.

In particular, predictable fracturing or plastic yielding of building components or materials can be intended to absorb energy of an event, reducing peak loads or displacements and thus lessening the risk of more significant failures.

One example of this type of predictable damage occurs in joints between wooden members and other parts of structure.

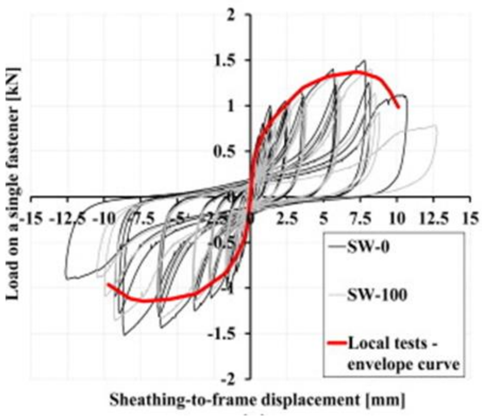

Figure 1: Pinched hysteresis loops in timber connections (Germano et al., 2015).

Where wooden members are connected to a flange or flanges by fastener(s) such as bolt or bolts, extreme forces can lead to crushing of wood against the fastener. The connection resistance associated with these different yielding failures has been well studied since its introduction by Johansen (Johansen, 1949).

This crushing/yielding can be a significant energy absorber. However, in an event such as an earthquake which induces cyclic forces or displacement, the wood member may be forced to move alternately relative to the fastener. Movement induced crushing in the first cycle opens up a cavity and allows a degree of "play" between the fastener and the wooden member. This play has a detrimental effect on the energy absorbency of the joint in subsequent movement cycles.

In timber buildings subjected to earthquake loadings, prior art structural joint solutions for resisting and damping seismic forces are mainly based on the yielding of the fasteners (bolts or dowels) in combination with crushing of the timber fibres by the fasteners. This achieves an amount of ductility and energy dissipation.

However, earthquake loads are cyclic, with repeated loading and unloading. The fibre crushing is irreversible, so the crushed timber area does not provide an immediate response in subsequent cycles of the event. This "slack" or "play" leads to a delay in the connection response, termed "pinching." The pinching means that the amount of energy available to resist earthquake excitation in subsequent cycles is limited.

2 PROPOSED PINCHING-FREE CONNECTOR

2.1 The PFC Concept

A novel connector was developed at the University of Auckland, New Zealand to overcome the pinching behaviour (Quenneville and Zarnani, 2016). The concept is based on the principle that the slack that occurs at every load cycle is absorbed or eliminated. By removing the slack in the connection, the fasteners would always be engaged with the timber to provide immediate resistance. Although the design of the joint could be made with slender or stocky fasteners, the ultimate amount of energy absorbed at every cycle would be controlled by the embedment strength of the wood, i.e. the Mode I resistance of the European Yield Model.

In the case of a PFC joint with small-diameter fasteners, the fasteners would initially deform and yield according to the EYM, exhibiting a Mode II or Mode III deformation behaviour. However as bending progresses, the fasteners source additional bending strength from their plastic capacity. At some stage, the fastener bending resistance surpasses the embedment resistance of the wood so that the governing mode of failure crosses-over from Mode II/III to Mode I eventually. Essentially, the bulk of the seismic energy would be absorbed through crushing of the timber fibres. This offers the advantage that the joint fasteners, even in

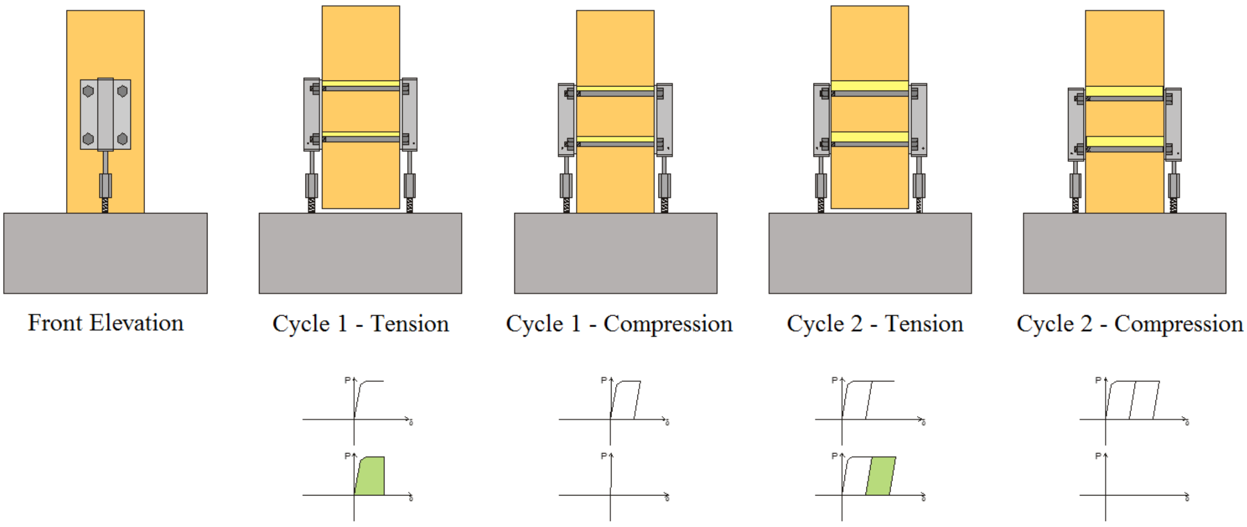

Figure 2: The proposed PFC used as hold-downs to eliminate pinching on each loading cycle.

their bent state, are available to mobilise the full energy-absorbing capacity of the embedment of the timber. This is shown in Figure 2 for one PFC concept.

One important requirement of the PFC is that there is sufficient resistance against one of the possible brittle failures (either row shear or group tear-out), even after a large amount of embedment failure (Quenneville and Mohammad, 2000). This is possible if the end-distances and bolt spacings in-row are large or if there are screws perpendicular-to-grain to prevent longitudinal shear failures.

2.2 The Prototype Device

Figure 3 illustrates a prototype of the PFC, where the device is used as a hold-down for a timber member. There are seven main components of the PFC as shown in the exploded view (Figure 3). The load path through these components is as follows. When the timber member uplifts, the bolt holes in the wood bear against and crush under the stationary bolts to accommodate the uplifting movement. The uplifting or vertical shear force is transferred from the bolts into the housing weldment. Within the housing, the tapered barrel transfers the vertical force but also creates a horizontal reaction on the split-wedges due to the tapered wedge-barrel interface. This horizontal force clamps the split-wedges onto the rod, so that a tight grip on the rod can transfer the vertical tensile force through the rod and through the connecting sleeve into the anchor.

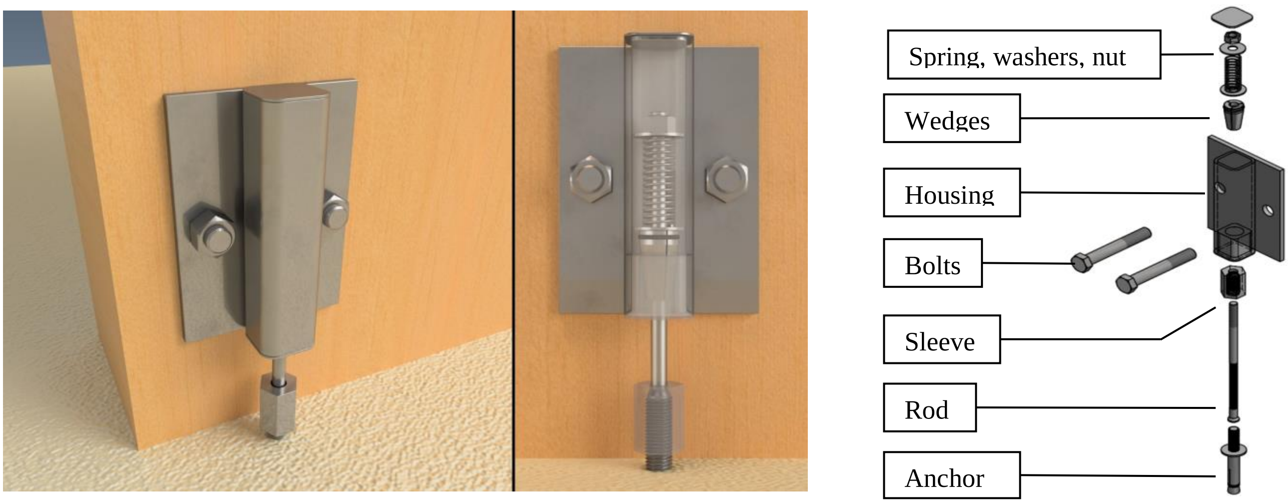

Figure 3: Prototype of the pinching-free concept, shown here as a hold-down for rocking shear walls.

During unloading, the timber member falls freely towards the ground with the housing and the bolts as one unit, since the housing is tightly fastened onto the timber by the bolts. The bolt shanks remain in contact with the wood fibres at the bottom of their elongated bolt holes all the time. In doing so, no slack can form between the bolts and the contacting wood fibres. As the housing travels downwards, contact is lost between the tapered barrel and the split-wedges, thus releasing any inward pressure on the wedges. Without the horizontal clamping force, the wedges disengage from the rod and become dislodged when the spring pushes them down into the receiving barrel that is now at a lowered height. The wedges lock onto the rod again, ready to resist tensile loading on the next uplift cycle. This describes the ratcheting behaviour of the PFC.

3 EXPERIMENTAL DEMONSTRATION

3.1 Testing Programme and Setup

The test programme comprised of three tests to demonstrate the various behaviour possible with the PFC. In the first test, the pinching issue was demonstrated by using standard steel brackets with 6-M10 low-strength bolts (as per Table 1). Of the three tests, this test more closely resembles the traditional design approach for ductile timber connections.

The aim of the second test was to eliminate this pinching by substituting the brackets with the PFC. Fewer and higher-grade bolts were also used for the PFC to reduce the extent of bending in the bolts, while maintaining an approximately similar capacity for the joint. This was necessary to prevent premature failure of the bolts at the threaded end (nut-side) that could occur due to the stress concentrations imposed on the fastener by the steel plate’s sharp edges. As the bolts no longer govern the capacity of the connection, the ultimate embedment strength of the wood could be mobilised.

In the third test, the fewest number of bolts were used, albeit the largest in diameter. Without any yielding in the bolts, this test examined whether a pure embedment failure or Mode 1 behaviour could be achieved to mobilise immediately the ultimate embedment strength of the wood, while having no pinching in the joint.

Figure 4 depicts the three types of connections tested. In all cases, the steel side-plates were all similarly sized and positioned on the wood. Figure 5 shows the loading protocol applied on the GLULAM specimens. The maximum displacements of the MTS loading arm were smaller for the PFC tests because of their ratcheting nature, which accumulate rapidly all the small-cycle deformation in the absence of slack.

Figure 4: Connections for Tests 1, 2 and 3 from left to right. See Table 1 for more details.

Table 1: Schedule of tests and their expected behaviour.

Test #	Connection	Fasteners	Wood Crushes	Bolts Yield	Pinching Occurs
Test 1	Brackets	6-M10 (Grade 4.8)	Yes	Yes	Yes
Test 2	PFC	4-M10 (Grade 8.8)	Yes	Yes	No
Test 3	PFC	2-M16 (Grade 8.8)	Yes	No	No

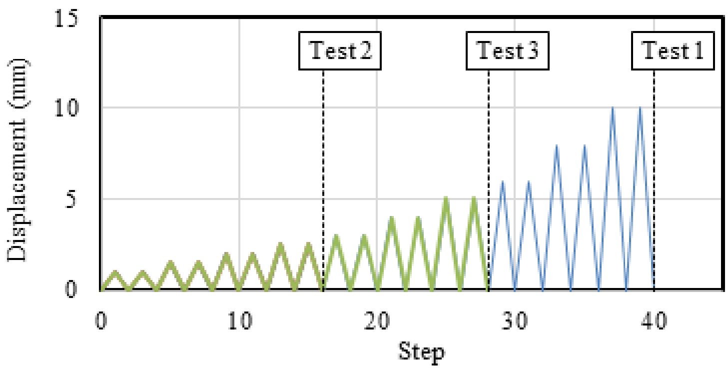

Figure 5: Load protocol planned for Tests 1, 2 and 3.

3.2 Test Results

Figure 6 shows the load-displacement curves foe each test and the pictures of the corresponding specimen at failure. Observations from Test 1 show the greatest bending in bolts and increasing amounts of slack on each loading cycle as deformation progressed. A relatively slower gain in strength was noticed in the backbone curve, as the full embedment capacity could not be reached even after 10 mm of deformation. This highlights the issue of connections with ‘many small-diameter’ fasteners in that a steady and reliable capacity is difficult to achieve without large deformation, whereupon pinching becomes a bigger issue that impairs the stiffness of the joint.

Pinching was eliminated in Test 2 which utilised the PFC. Fewer bolts were used in this connection, but less bending was observed as they had higher yield strengths. As pinching was no longer an issue, larger displacements could be achieved without any loss of stiffness. Furthermore, the connection resistance was able to reach a plateau of 150 kN as the full embedment capacity of the wood was achieved. In this case, the test was terminated prematurely due to brittle failure of the wood.

Test 3 applied the PFC with two large-diameter, high-strength bolts. This configuration contrasted with the traditional design philosophy to use ‘many small-diameter’ fasteners (as in Test 1). However, the full embedment strength could be achieved much earlier – as indicated by the plateau in Figure 6 – while maintaining a high ductility capacity.

Without pinching, this connection provided a stiff and immediate response on each loading cycle. The stiffness arose from friction initially but eventually was governed by the elastic deflection of the wood. The caveat for high stiffness on the very first cycle is that the device should be screwed tightly into the anchor at the time of installation to ensure that any slack is already eliminated when the device first engages. This connection – while different from the traditional approach – could achieve the greatest displacement ductility of 10 in this test without suffering from any degradation of strength or stiffness.

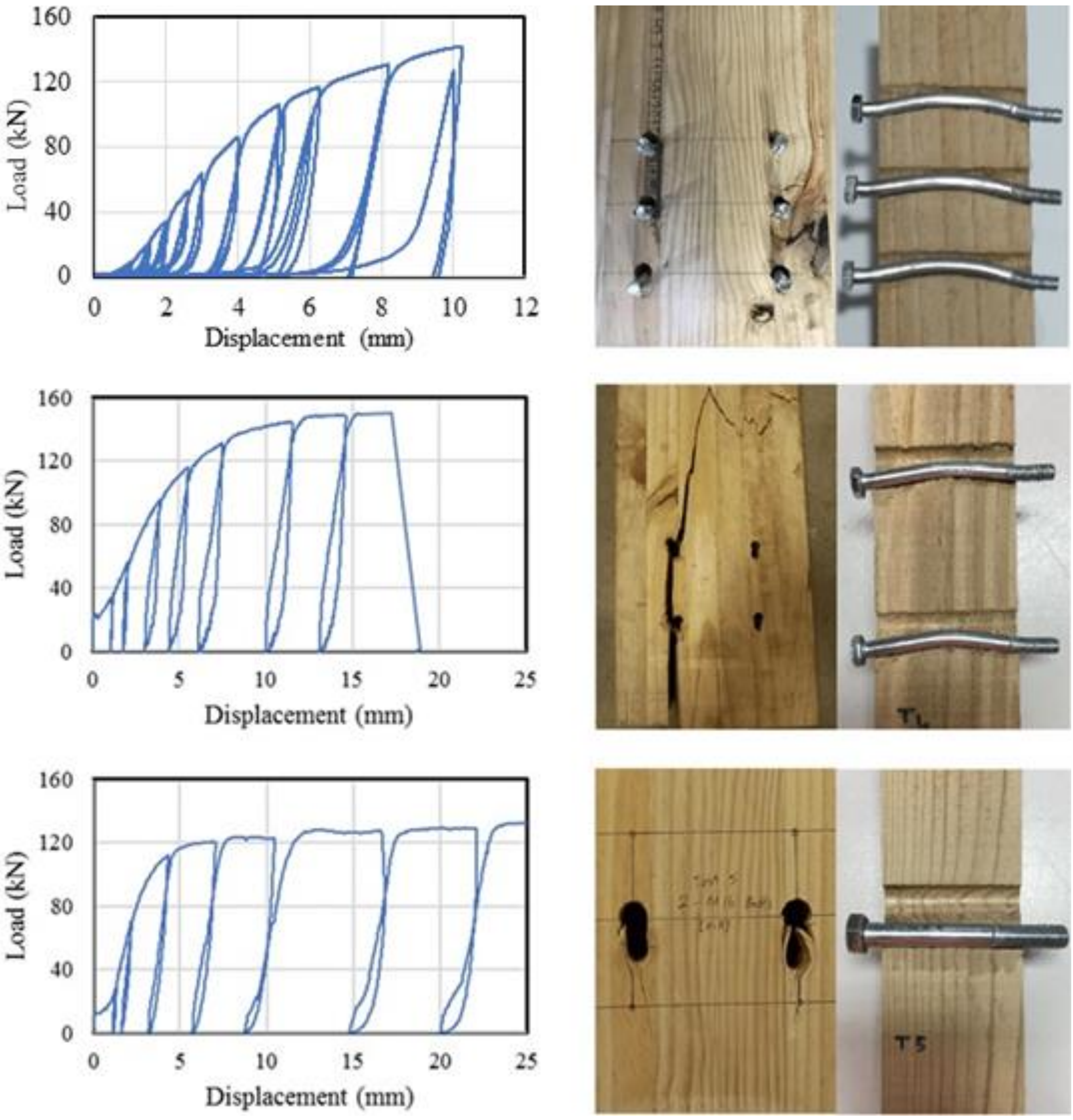

Figure 6: Load-displacement graphs and specimens at the end of the tests. Note the different x-axis scales.

4 SIMULATING SEISMIC PERFORMANCE WITH THE PFC

4.1 Numerical Models and Inputs

The SAP2000 software was used to investigate the behaviour of a rocking shear wall equipped with the PFC. Figure 7 shows the timber shear wall that is 1200 mm wide by 2700 mm tall, with a lateral mass of 10 tons assigned to the top of the wall. Gap elements were used to simulate the foundation, while horizontal restraints were assigned at the toes of the wall to serve as shear keys.

Friction-Spring Damper link elements that could be calibrated to work only in tension were used to model the ratcheting behaviour of the PFC. The backbone curve was idealised from Test 3 (Figure 6) as an elastic-perfectly plastic shape. Crushing was assumed to initiate after 2 mm of elastic deformation.

To model the ordinary brackets, multi-linear plastic elements (Hashemi et al., 2016) were connected in series to elastic cable elements. The cable elements made it possible to model the slack that occurs in ordinary brackets due to elongated bolt-holes. The backbone curve of the plastic element was based on Test 1

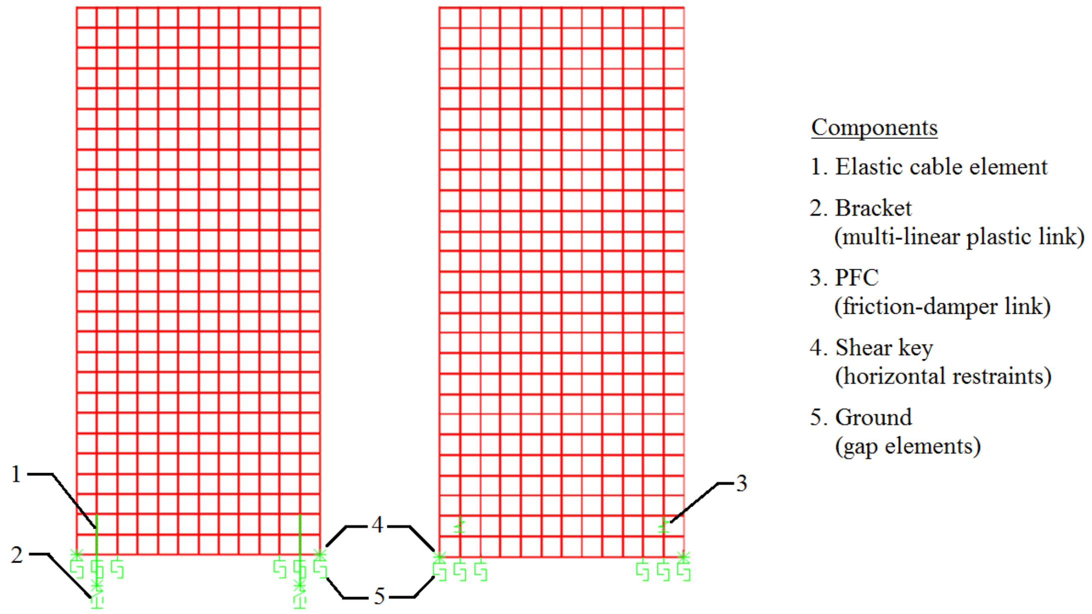

Figure 7: Rocking timber shear walls equipped with: ordinary brackets (left) and the PFCs (right).

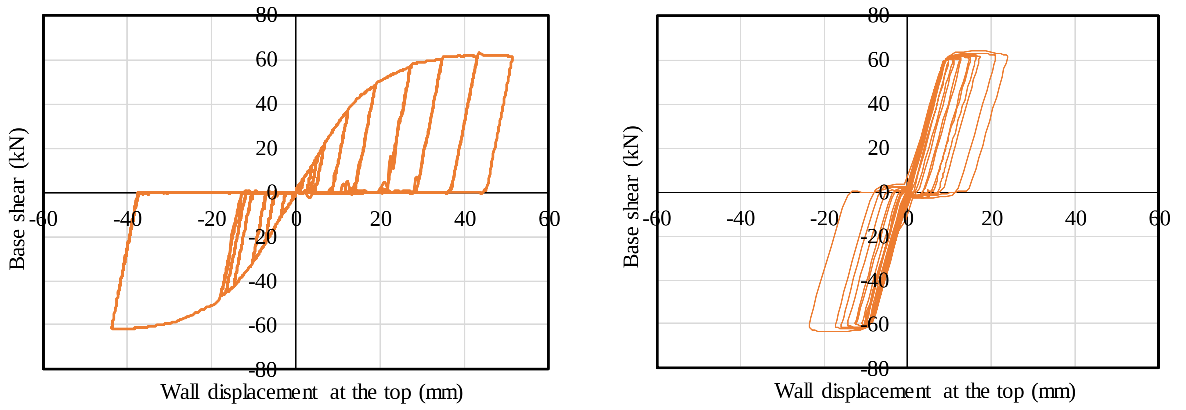

Figure 8: Example of hysteresis graphs for the walls using ordinary brackets (left) and the PFCs (right).

(in Figure 6) and with no strength degradation. In both cases, the ultimate capacities of the connections plateau at 150 kN. Figure 8 shows an example of the hysteresis loops produced by the rocking walls when using bracket connections and when using pinching-free connections.

Table 2 shows the 10 ground motions used as input excitations. They were scaled to match the New Zealand design spectrum with a site hazard factor of 0.4, site soil class D and a return period of 500 years representing the ULS design level earthquake (Standards New Zealand, 2004).

4.2 Results of Simulations

Figure 9 shows the displacement time-histories for the Christchurch and Kaikoura ground motions. For the bracket connections, it can be observed that larger swings in displacements persisted long after the peak acceleration demands were over, as expected from a 'loose' connection possessing significant slack. In contrast, the wall equipped with the PFC underwent smaller-amplitude and higher-frequency vibrations, which resemble stiffer connections. This was expected because the PFC provides stiff and immediate resistance to any uplift (i.e. any movement that pushes the wall further off-centre) and being a tension-only device, allowed the wall to return to its upright position without any resistance. With the PFC, vibrations after the peak acceleration demands were substantially smaller and mostly elastic.

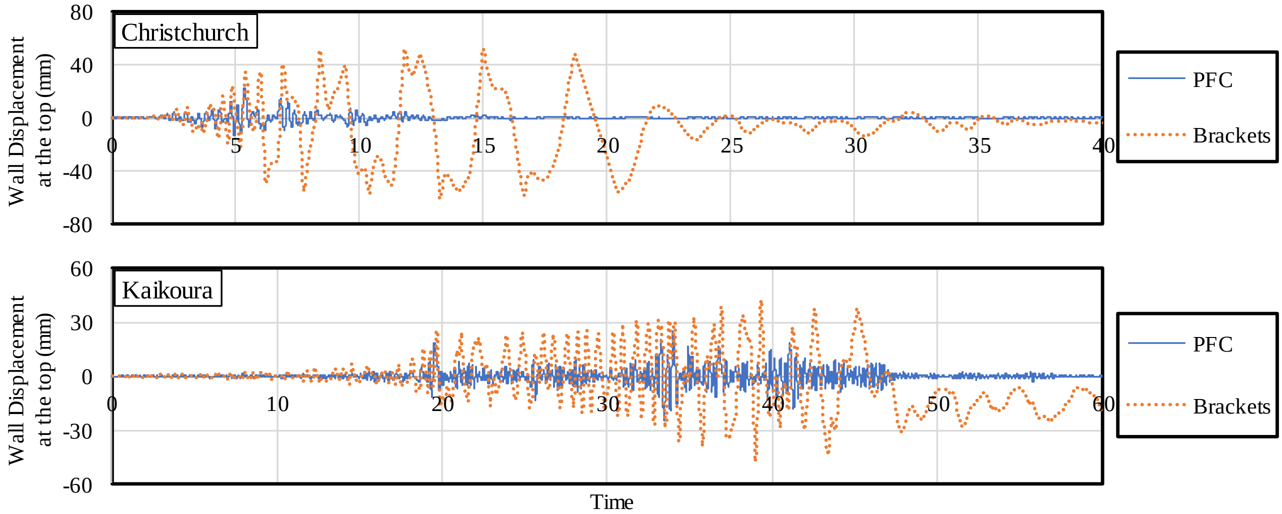

Figure 9: Displacement time-histories to compare the behaviour of the PFC against the bracket connections.

Table 2: Results of non-linear time history analyses for 10 different ground motions.

Input Ground Motions				**Peak Displacements (mm)**		**Optimised PFC**	
Event	**Station Name**	**Year**	**Scale Factor**	**Brackets 150 kN**	**PFC 150 kN**	**Capacity (kN)**	**Base-Shear Reduction, k_μ**
Chi-Chi	TCU065	1999	1.32	170	33	73	4.2
Christchurch	Botanical Gardens	2011	1.08	62	22	92	3.6
Imperial Val.	El Centro Diff. Array	1979	1.11	43	18	88	3.1
Kaikoura	Ward Fire Station	2016	0.74	48	25	73	5.7
Kobe	Takarazuka	1995	0.88	40	15	105	1.9
Kocaeli	Meteorological Office	1999	1.33	43	42	144	2.3
Landers	Lucerne	1992	1.63	51	33	118	5.3
Loma Prieta	LGPC	1989	0.77	68	18	82	3.7
Northridge	Saticoy Street	1994	0.90	48	15	72	5.0
Tohoku	Sendai (MYG013)	2011	0.65	81	16	66	3.3

Table 2 shows that the peak displacements were 3 times smaller on average with the PFC than with the brackets. As peak displacements are reduced significantly by the PFC, it may be overly-conservative to design PFC with the same ultimate capacity as standard brackets. Instead, the capacity of the PFC could be reduced to achieve a given design drift. Referring to the Christchurch excitation for example, the peak displacement of 62 mm attained by the 150 kN brackets could be similarly achieved by a reduced PFC capacity of 92 kN. On average, the ultimate capacity of the connections could be reduced by 39% to 91 kN (i.e. to 61% of the original 150 kN). With these optimised PFC capacities, elastic analyses were also performed to obtain the elastic base-shears. The reduction in base-shears (found as the ratio between the elastic to inelastic base-shears) ranged in between 1.9 to 5.7. This shows that non-negligible reduction in base-shears could be attained for inelastic design while keeping peak displacements at acceptable limits.

The benefit of a reduced connection capacity flows onto reduced structural member sizes, assuming that capacity design principles are adhered to. In addition, a predominant and predictable failure Mode 1 implies that smaller over-strength factors are possible, as the connection strengths are well-defined by the embedment strength which plateaus relatively early. This may imply further cost savings with smaller structural members equipped with the pinching-free connection.

5 CONCLUSIONS

This paper presents a new pinching-free connector (PFC) for timber members resisting cyclic loading. An experimental demonstration was undertaken to validate the performance of the PFC when used as hold-downs. Ordinary steel brackets were also tested to compare and highlight some issues in the traditional approach to design. Finally, numerical simulations were performed to compare the potential benefits of the PFC as against standard steel brackets when applied as hold-downs in rocking timber shear walls.

Under repeated cycles of tensile loading, the bracket connection (with 6-M10, Grade 4.8 bolts) was shown to suffer from a relatively slower uptake in strength as well as poor cyclic behaviour that exhibited pinching, i.e. delayed resistance due to the slack formed from previous cycles of deformation. In contrast, the PFC (with 4-M10, Grade 8.8 bolts) could eliminate pinching and at the same time achieve a load plateau. The load plateau indicated a transition from Mode II/III to Mode I of the European Yield Model, where the full timber embedment strength could be achieved even with bent fasteners.

In the final test, the PFC utilised an alternate configuration of fasteners with 2-M20 (Grade 8.8) bolts. Although this connection used the smallest number of fasteners, the behaviour gained from using strong and large-diameter fasteners was an outright Mode I resistance that mobilised the full timber embedment strength immediately and continuously. This connection produced the fastest gain in strength and stiff responses on every loading cycle. The connection capacity was well-defined and predictable. It also achieved the most ductile performance with a displacement ductility of 10, without any strength or stiffness degradation.

The numerical simulations utilised 10 ground motions scaled as per the New Zealand Standard NZS1170.5. Compared with traditional brackets, the PFC indicated 3 times reduction in peak displacements on average, as well as substantially muted post-peak vibrations, which were mainly elastic. In contrast, the rocking wall equipped with the bracket connections demonstrated larger swings in displacements that persisted long after the peak ground accelerations had occurred. These large swings could be attributed to the slack arising from the connection, as the loss of stiffness rendered the structure sensitive to smaller accelerations.

From the simulations, it was also observed that for a given design drift, a standard bracket could be replaced with a PFC of a smaller capacity to facilitate inelastic design. In this case, the PFC could be reduced to 61% of the brackets ultimate capacity. With a reduced PFC, the reduction in base-shears ranged from 1.9 to 5.7. This shows that non-negligible reduction in base-shears are possible while keeping peak displacements at acceptable limits. With a lower connection capacity, cost savings are possible from reduced structural member sizes via capacity design. Further savings are possible due to lower over-strength factors, since the 95th percentile failure load is more clearly defined and predictable for pure embedment failure.

With the PFC, performance advantages can be gained in terms of reliable strength, consistent stiffness, smaller displacements and superior ductility when compared to the traditional design approach which uses steel brackets and small-diameter fasteners. By preventing pinching, it is shown that timber structures do not have to suffer from poor dynamic performance for the sake of a minimum amount of ductility.

ACKNOWLEDGEMENTS

The authors acknowledge the University of Auckland for providing funding for the research and the tests. The authors are also grateful for the advice and assistance of Mark Byrami in conducting the tests.

REFERENCES

Germano, F., Metelli, G. & Giuriani, E. 2015. Experimental results on the role of sheathing-to-frame and base connections of a European timber framed shear wall, *Construction and Building Materials*, Vol 80.

Johansen, K.W. 1949. Theory of timber connection, *International Association for Bridge and Structural Engineering*, Vol 9 249-262.

Quenneville, P. & Zarnani, P. 2016. *Pinching-free hold down for timber shear walls.* Application No. 724903, Filed 4 October 2016, NZ IP Office.

Quenneville, J.H.P. & Mohammad, M. 2000. On the failure modes and strength of steel-wood-steel bolted timber connections loaded parallel-to-grain, *Canadian Journal of Civil Engineering*, Vol 27(4) 761-773.

Hashemi, A., Masoudnia, R. & Quenneville, P. 2016. A numerical study of coupled timber walls with slip friction damping devices, *Construction and Building Materials*, Vol 121.

Standards New Zealand. 2004. *Structural design actions. Part 5: Earthquake actions*, New Zealand (NZS 1170.5: 2004 incorporating Amendment No. 1). Retrieved from https://shop-standards-govt-nz/ on 19th October 2018.